At-wavelength Alignment and Testing of the 0.3-NA MET Optic

Reaching diffraction-limited imaging, and beyond

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International SEMATECH Project Manager

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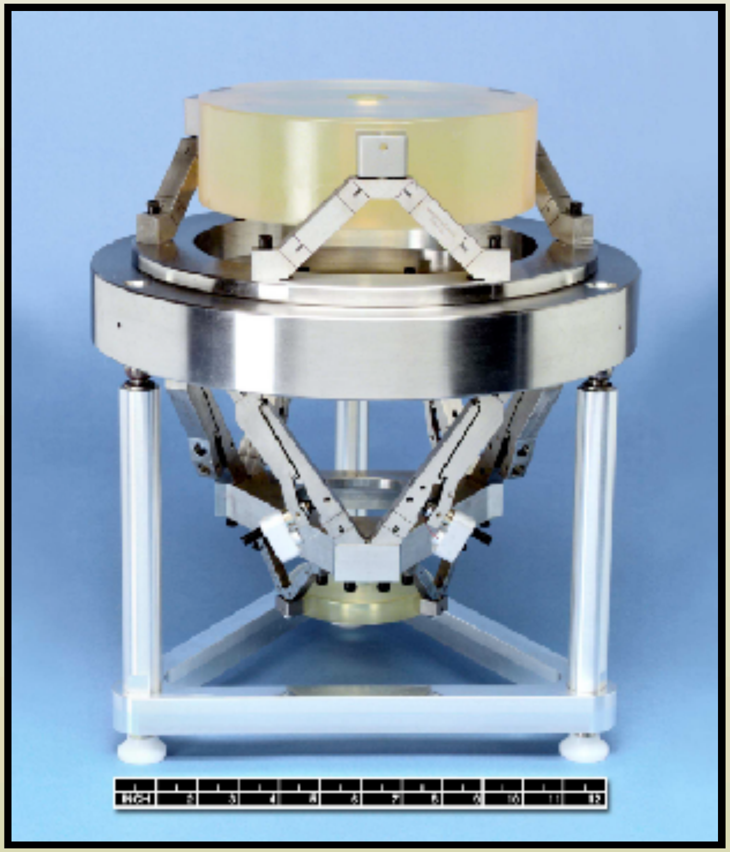
Project Goals

Create and operate an EUV resist-testing facility with imaging down to ~15 nm, and several unique capabilities.
(see Naulleau, *et al.* *)*

For Optimal EUV imaging, wavefront tolerances are ~0.1 nm

Ultra-high accuracy
EUV interferometry

- Many opportunities for learning
- Extensions of known techniques
- Opportunity for cross-comparison



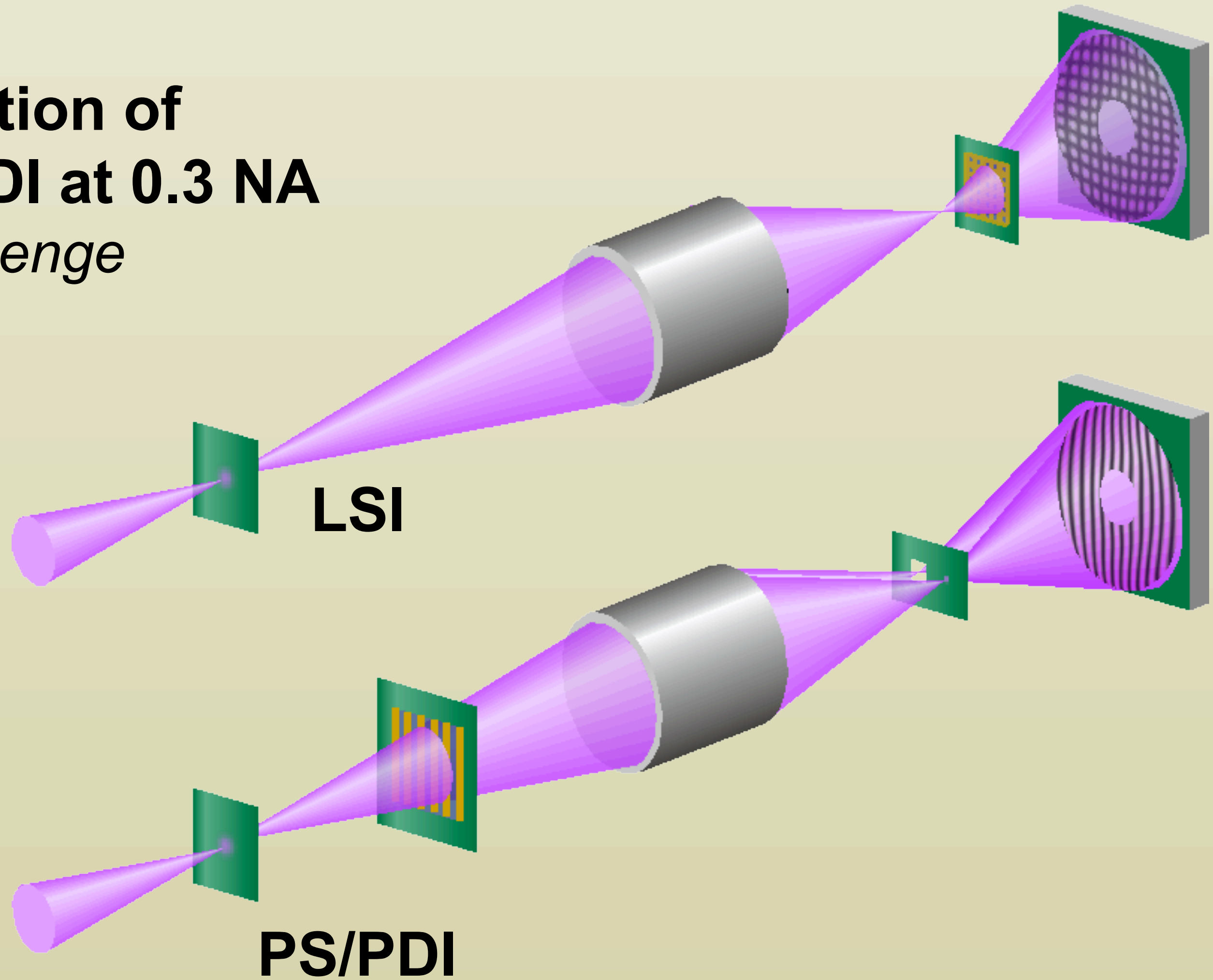
The MET (Set-2)
(shown here with surrogate optics)
Made by Zeiss.
Assembled and pre-aligned by Lawrence Livermore.

At-wavelength MET-testing overview

EUV interferometry, alignment and characterization

Successful application of shearing and PS/PDI at 0.3 NA

a huge technical challenge



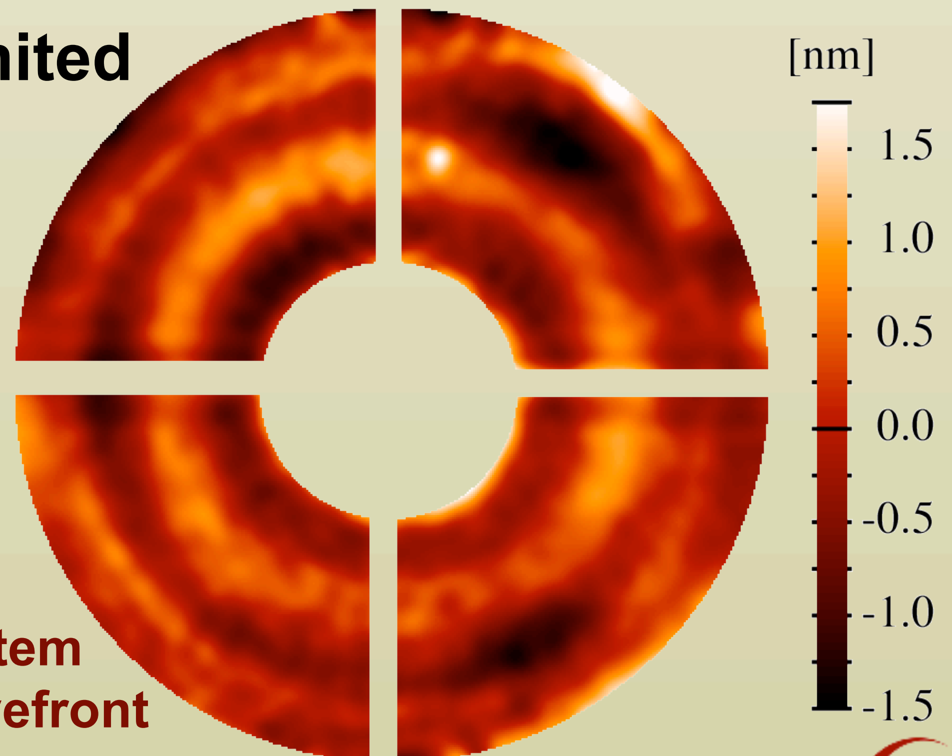
At-wavelength MET-testing overview

EUV interferometry, alignment and characterization

Successful application of
shearing and PS/PDI at 0.3 NA

Optic reached diffraction-limited wavefront performance

minimum σ_{37} **= 0.55 nm,** $\lambda_{EUV}/24$



system wavefront

At-wavelength MET-testing overview

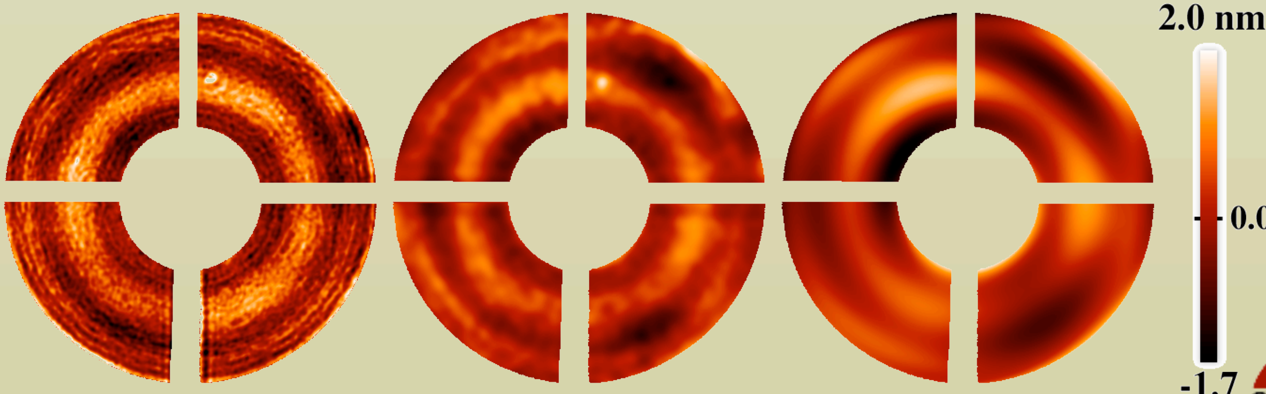
EUV interferometry, alignment and characterization

Successful application of
shearing and PS/PDI at 0.3 NA

Optic reached diffraction-limited
wavefront performance

Visible PSDI • EUV PS/PDI • EUV LSI intercomparison

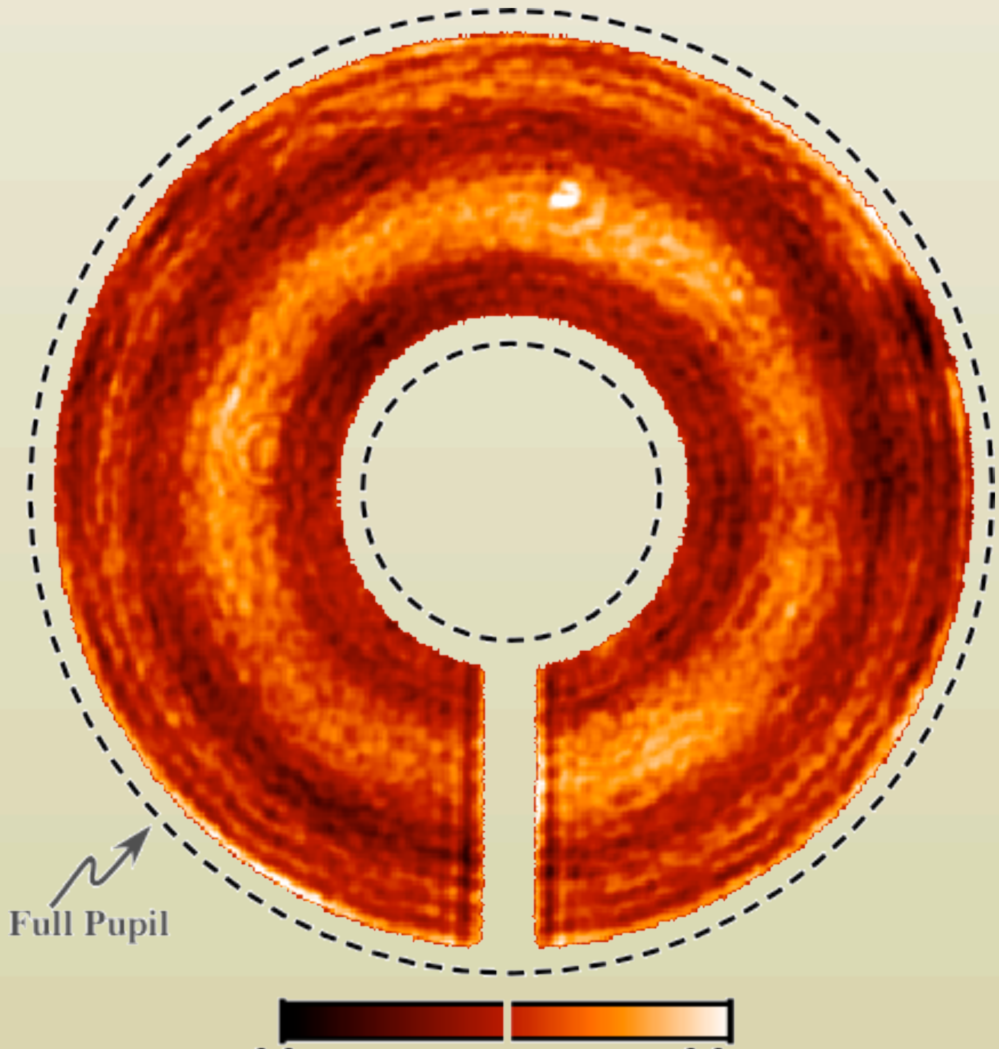
complicated by alignment issues



Three high-accuracy interferometers

lensless PSDI	LSI (shearing)	PS/PDI
LLNL *Lawrence Livermore*	***LBNL*** *Lawrence Berkeley*	***LBNL*** *Lawrence Berkeley*
visible-light λ = 532.2 nm	EUV 13.5 nm	EUV 13.5 nm
accuracy target $\sim\lambda_{vis}/5322$	$\sim\lambda_{EUV}/135$	$< \lambda_{EUV}/135$
-Essential for single-element testing. -Convenient for system alignment. -Operates at air.	-Fast, easy to perform. -High accuracy requires careful calibration & analysis. -Used for field measurement and alignment.	-The high-accuracy standard. -Working with sub-30-nm pinholes for 0.3 NA testing is a challenge. -Used for accuracy validation and higher spatial-*ƒ* response. -Covers the full pupil

Final visible-light measurement of the MET

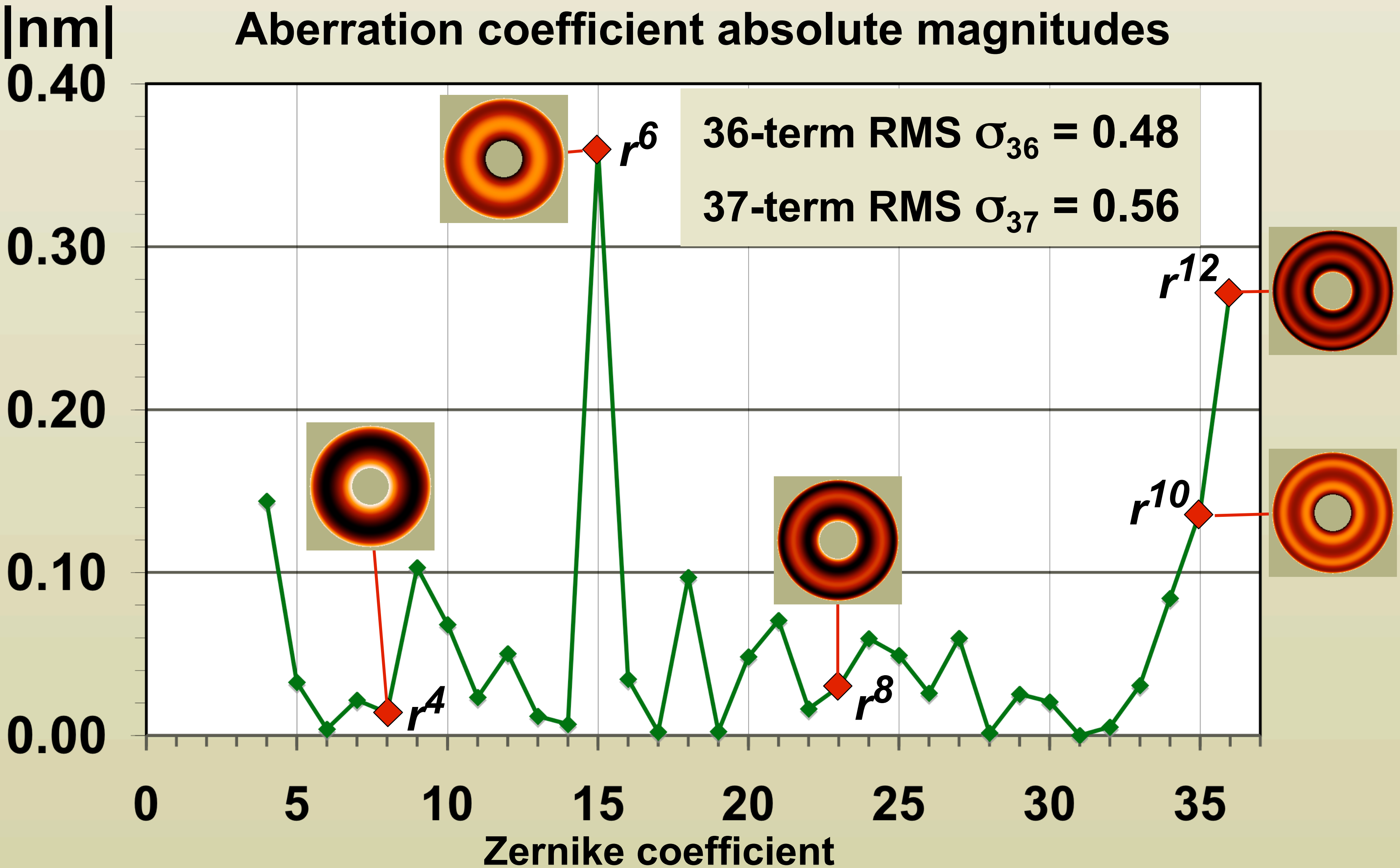


Data courtesy Don Philion, LLNL

astigmatism, coma, and spherical aberration were "zeroed" by alignment

10 < *r* < 26 mm	
0.56 nm	37-Zernike fit
0.15 nm	astigmatism
0.12 nm	trifoil
0.10 nm	coma
0.05 nm	spherical ab.
0.49 nm	h.-o. spherical

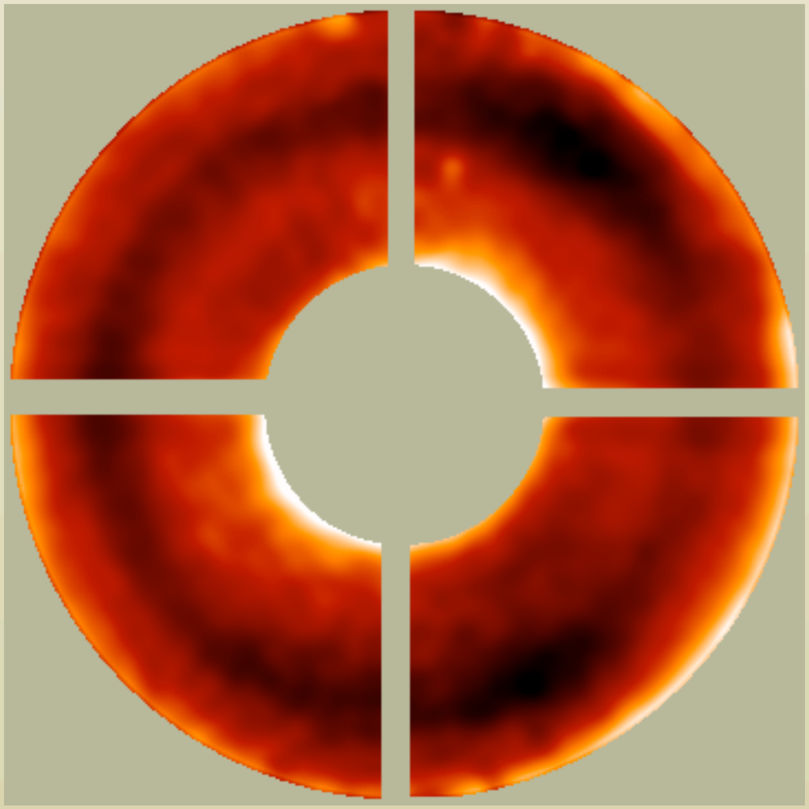
Higher-ordered spherical aberration is significant

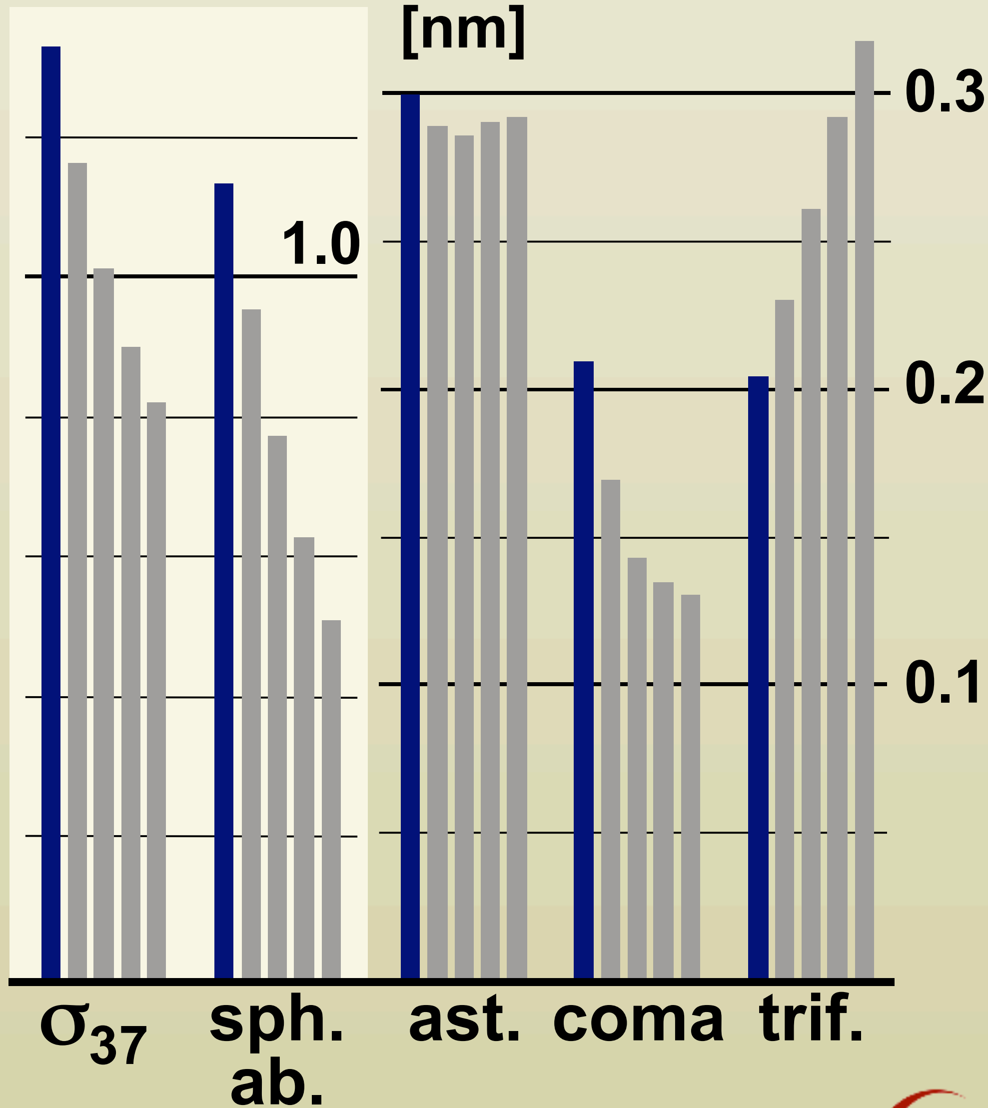


MET Set-2 visible-light data, LLNL/LBNL

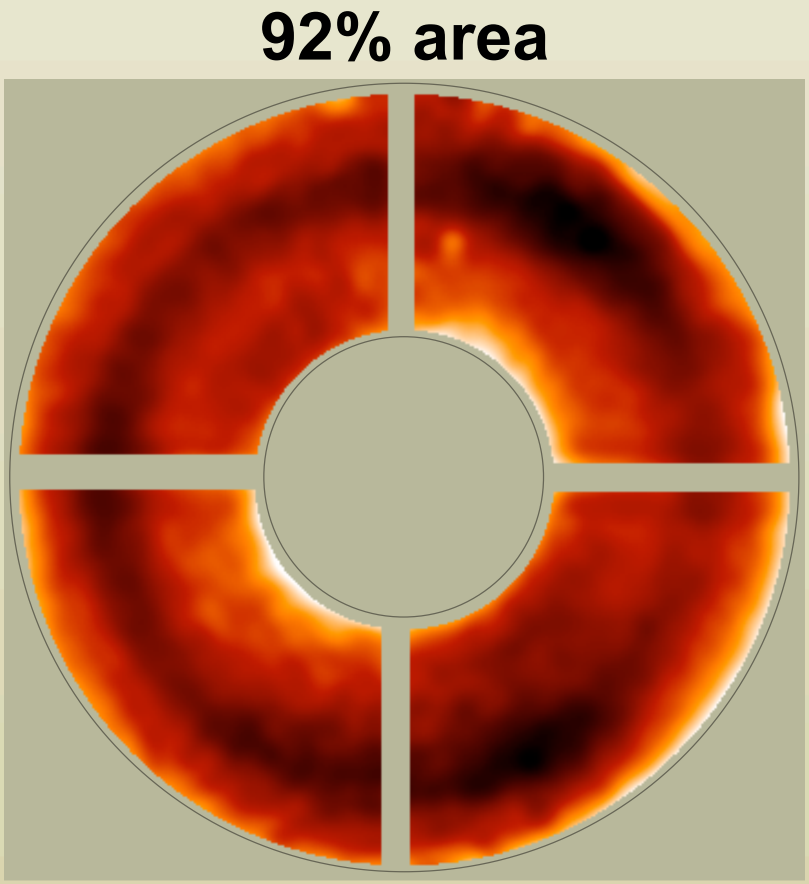
The importance of measuring the whole pupil

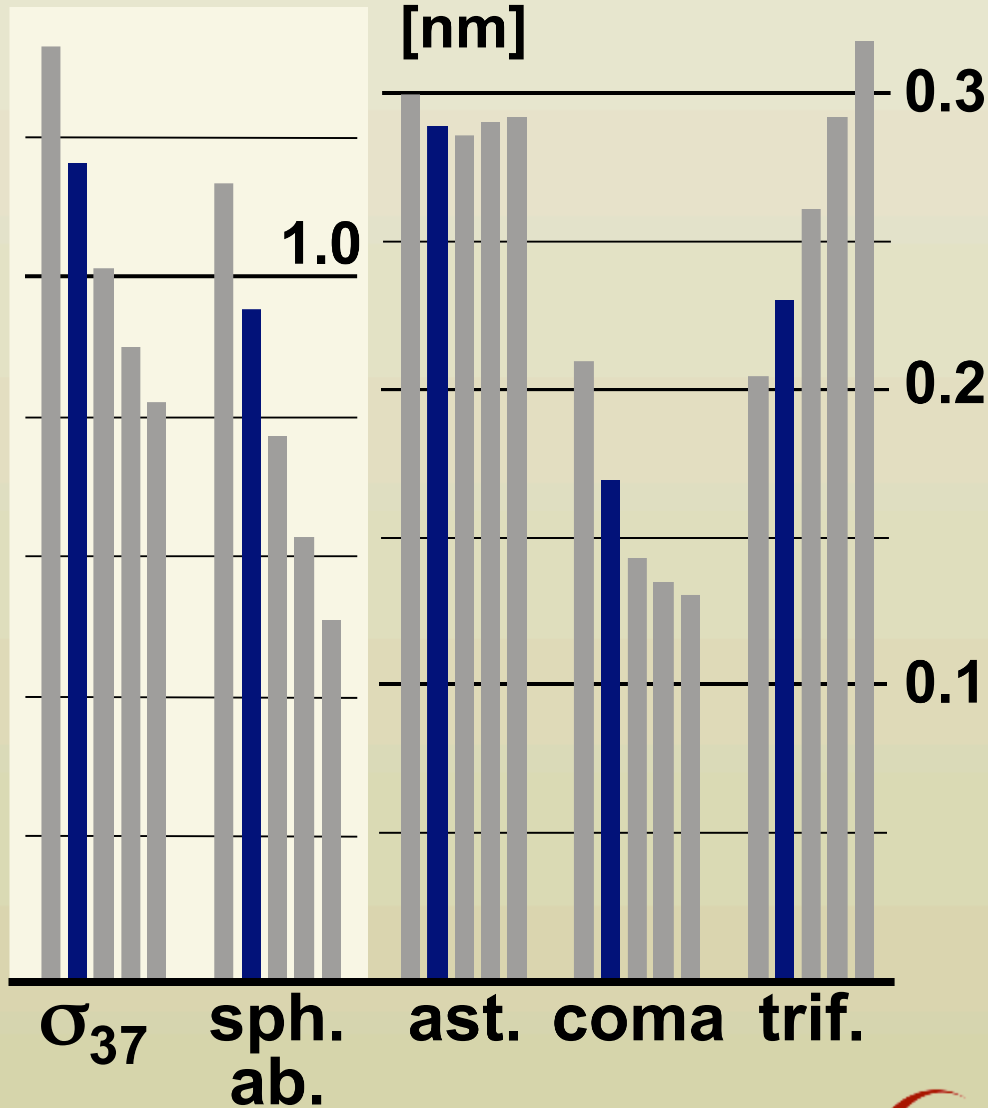
99% area





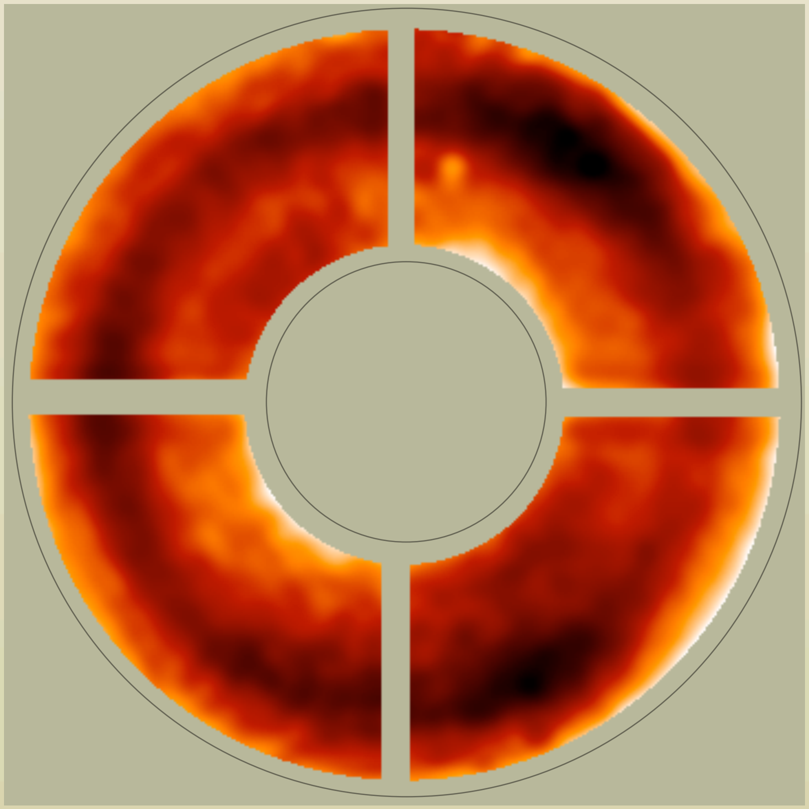
The importance of measuring the whole pupil

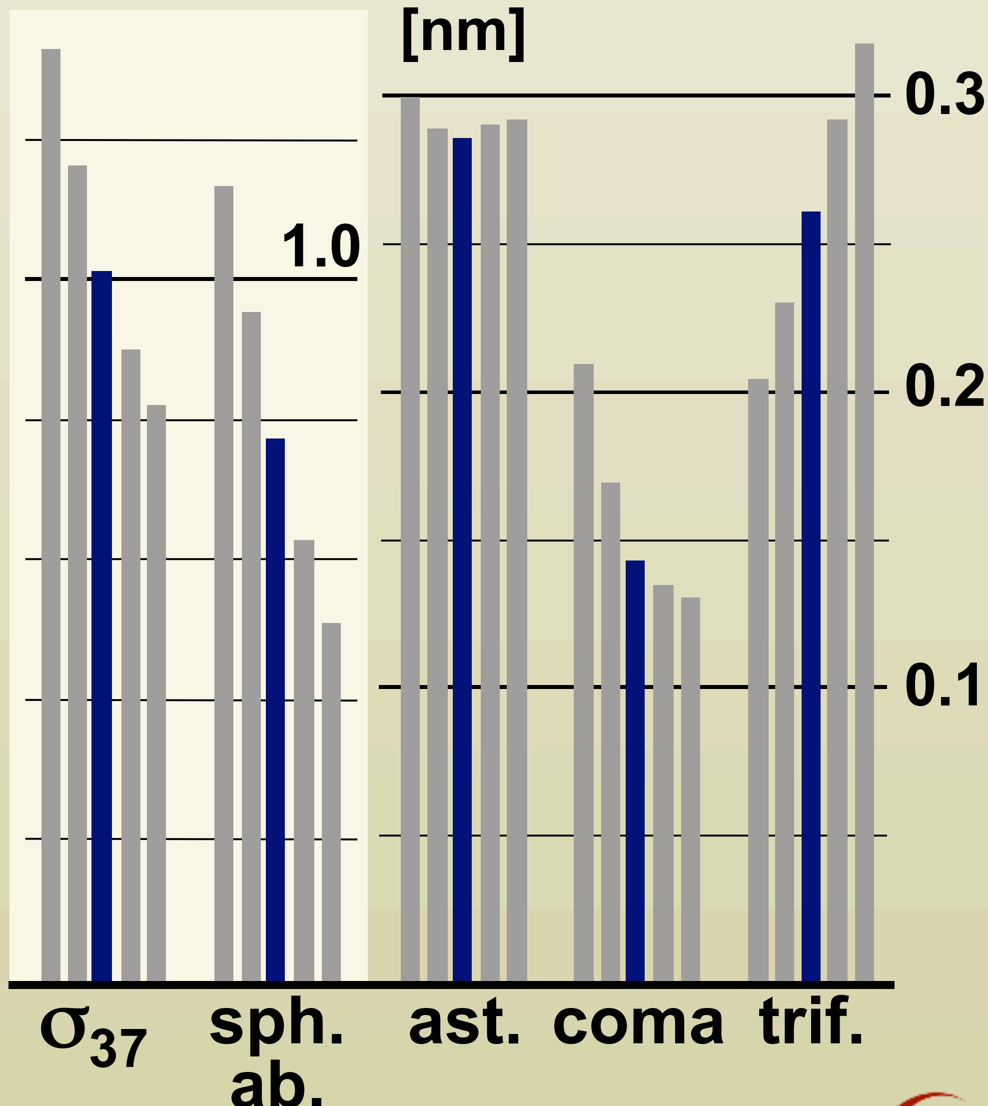




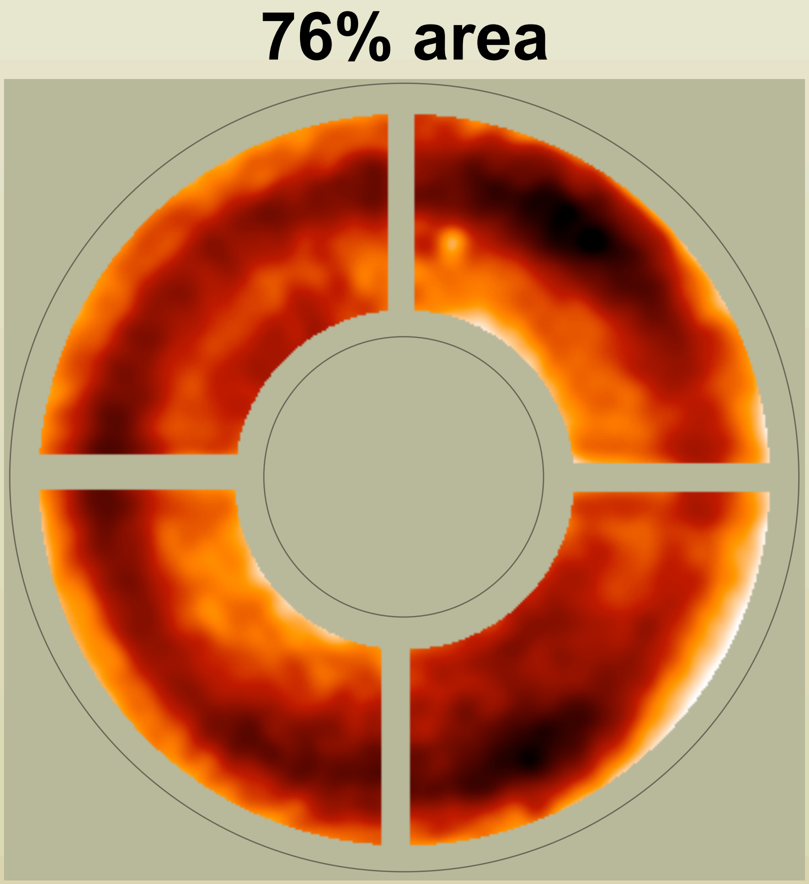
The importance of measuring the whole pupil

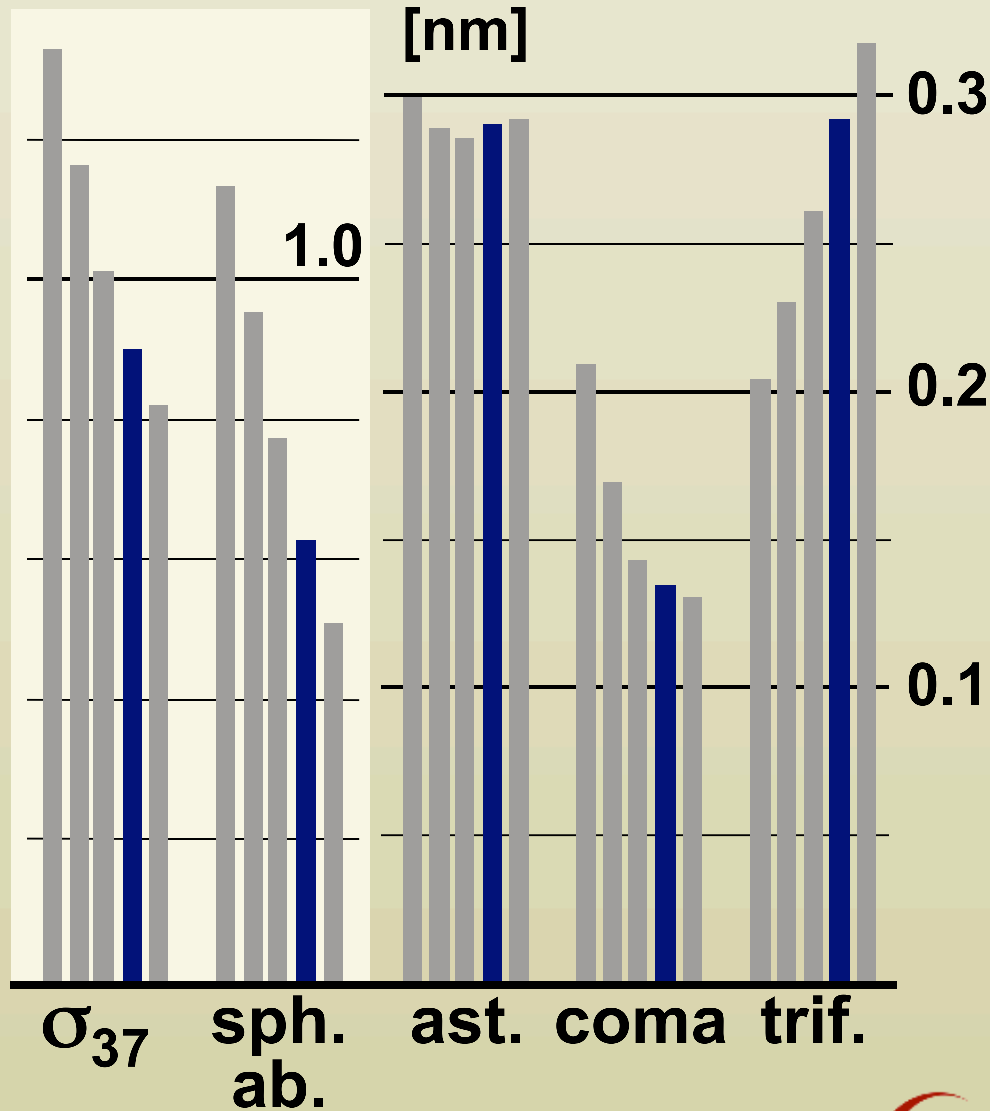
84% area





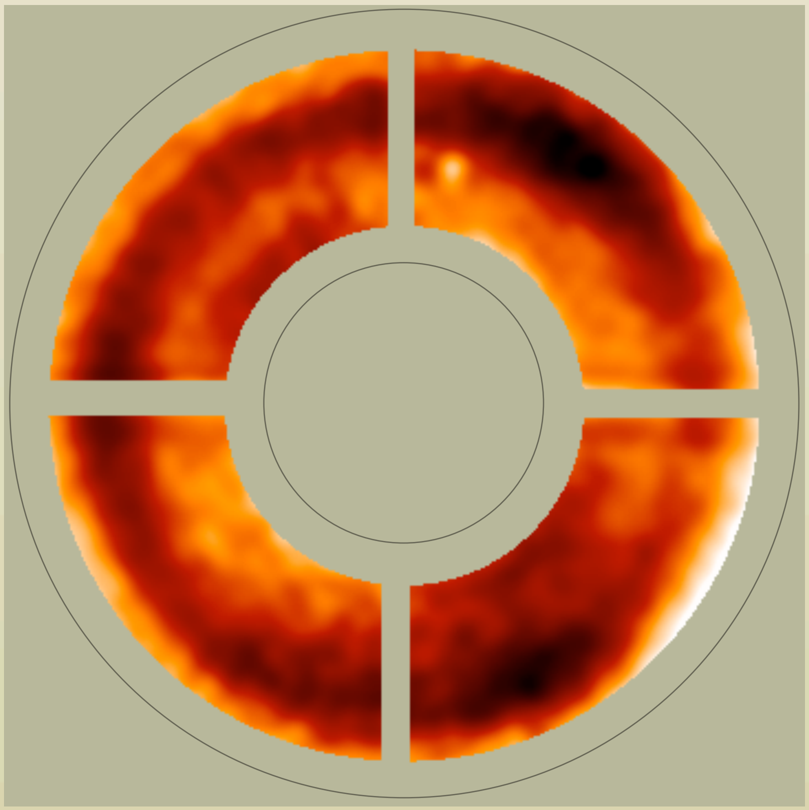
The importance of measuring the whole pupil

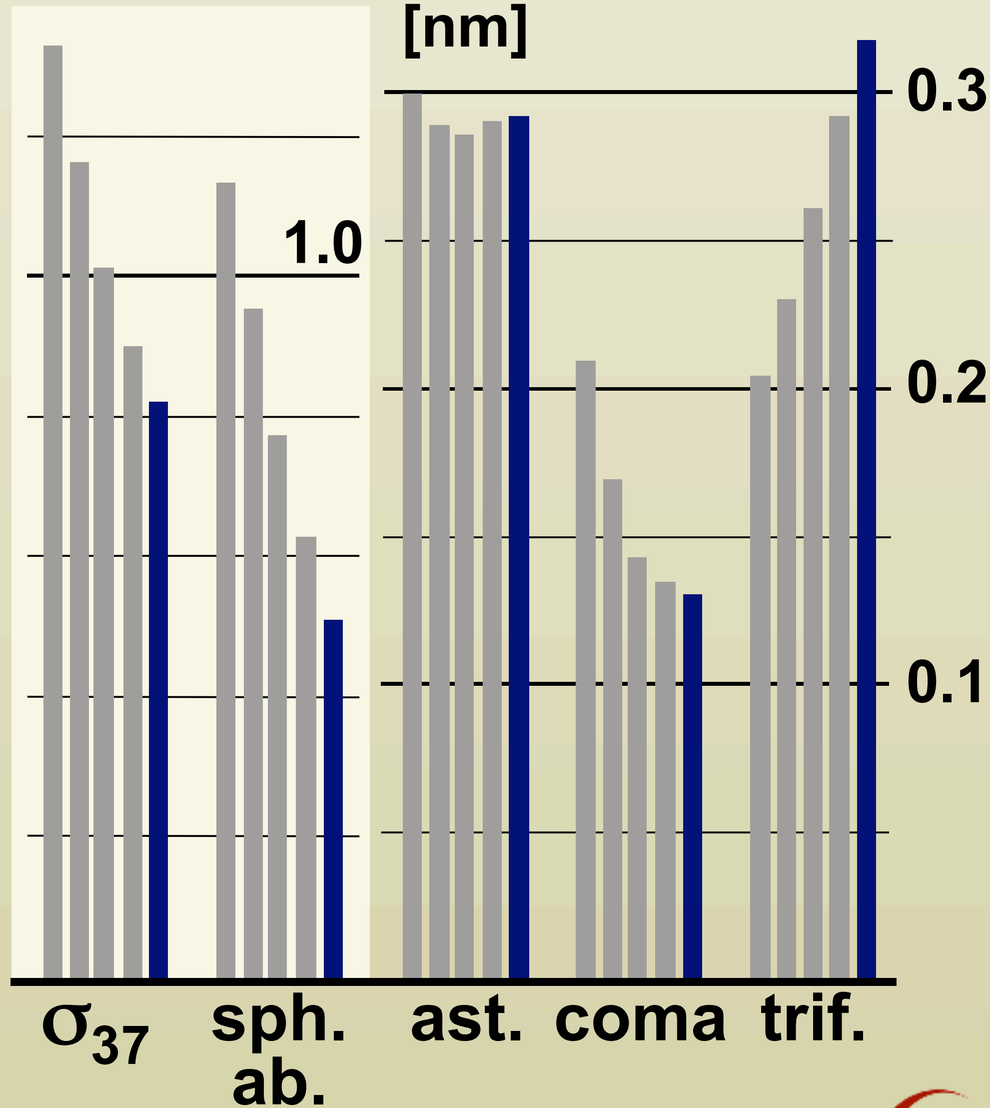




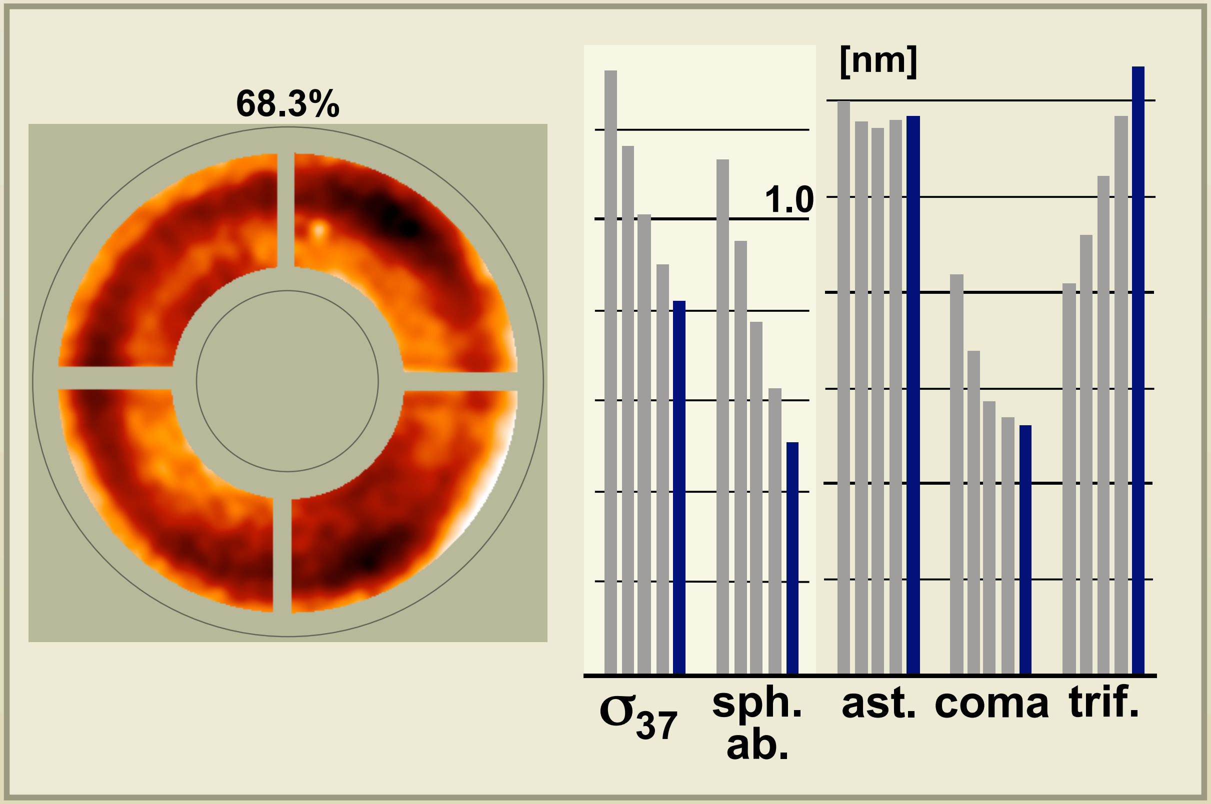
The importance of measuring the whole pupil

68% area



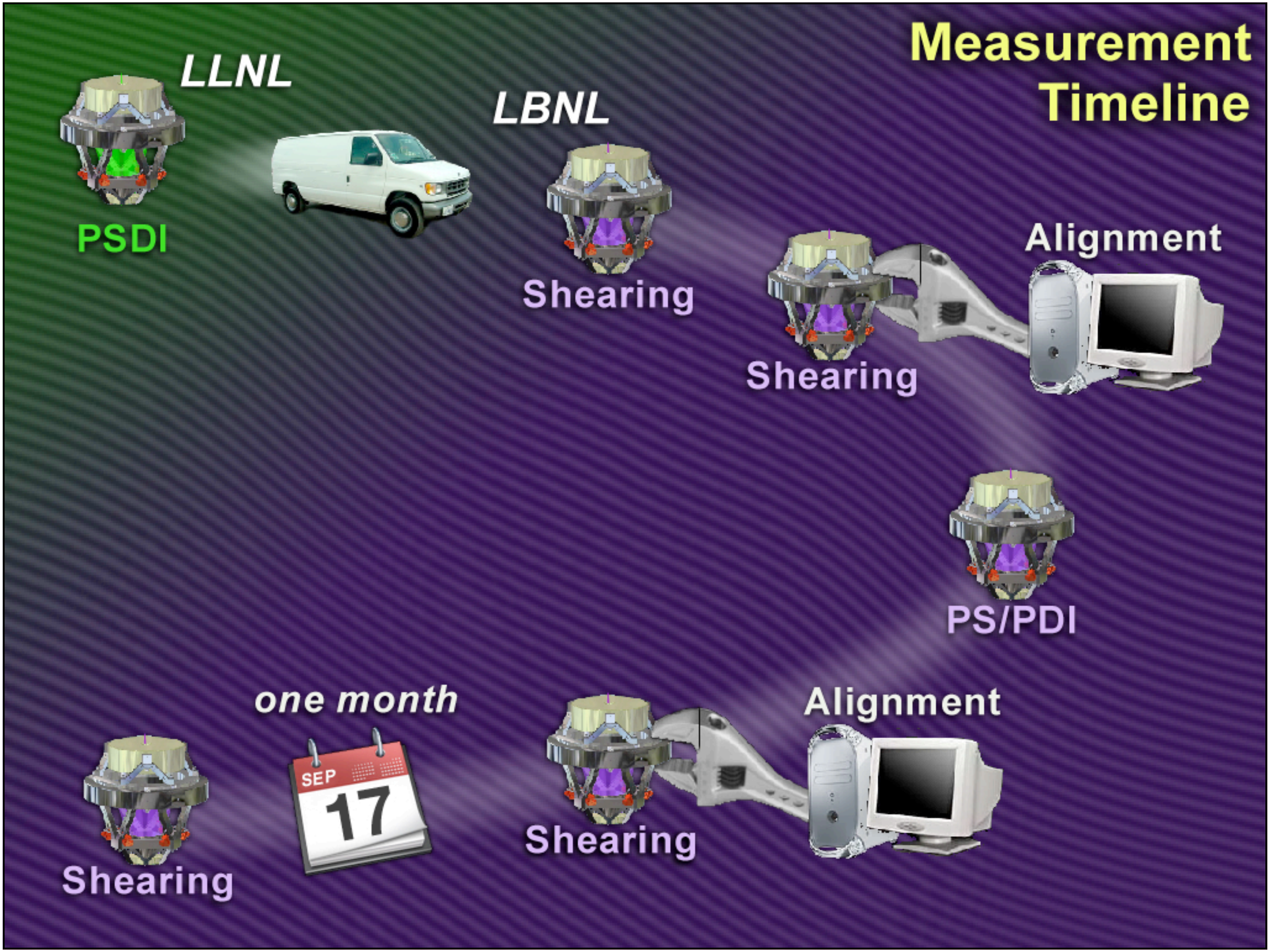


The importance of measuring the whole pupil



- We cannot predict the aberrations outside of the measurement domain
- Values depend strongly on the pupil area.

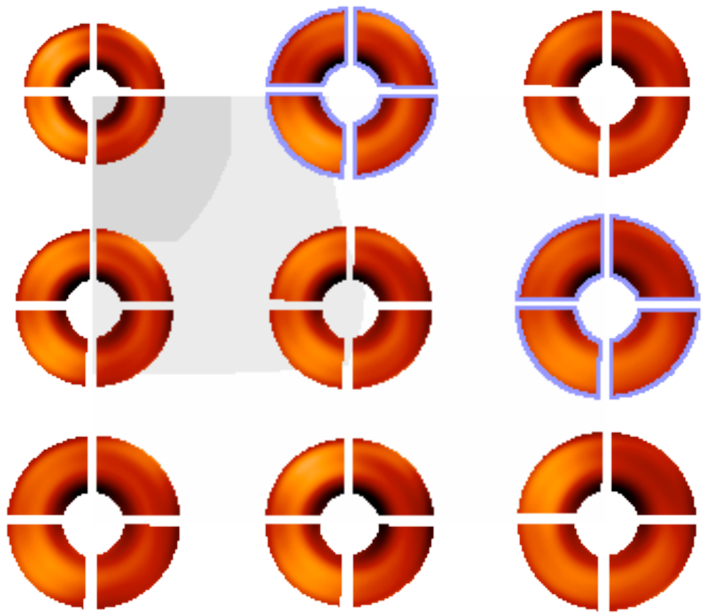
Modeling based on only part of the pupil gives you only part of the answer



Measurement
Timeline
LLNL
PSDI
LBNL
Shearing
Shearing
Alignment
PS/PDI
one month
SEP
17
Shearing
Alignment
Shearing

Initial shearing measurement at 20°C

Field measurement



M030702 note: diameter = magnitude

σ_{37} [nm]

1.04	1.23	1.22
1.15	1.19	1.32
1.27	1.23	1.31

$\lambda/13$

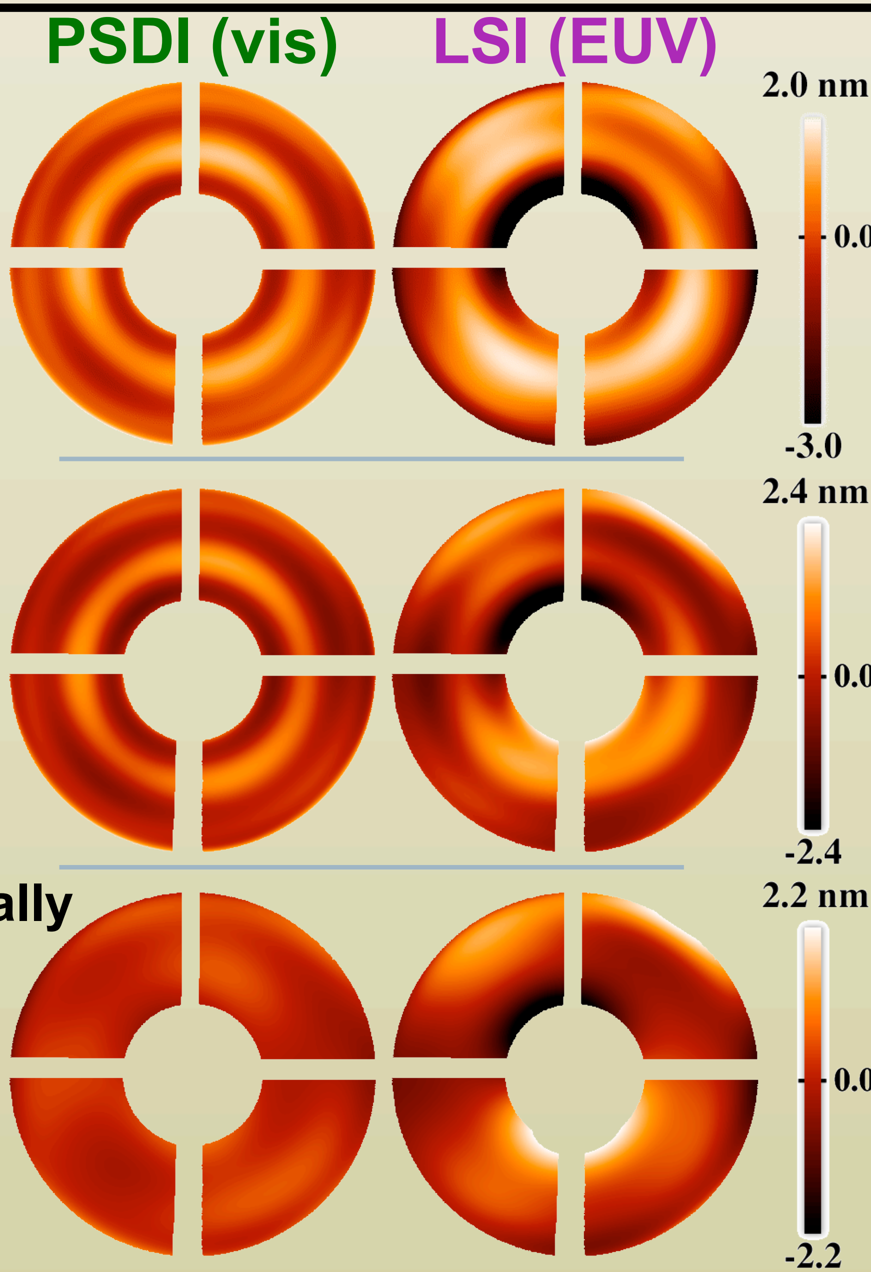
central field point [nm]

astig = 0.29
coma = 0.45
sph. ab. = 0.86
trifoil = 0.09
h.-o. sph. = 0.38

In our first EUV measurements at 20°C, a large, *unexpected* primary spherical aberration was dominant.

Higher-order spherical aberration was also present.

Visible-light PSDI and initial EUV LSI comparison



[nm]

full 37-term wavefront

	visible	EUV LSI	difference
σ_{37}	0.55	1.19	1.13
PV	3.31	6.47	6.53

spherical aberration removed

	visible	EUV LSI	difference
σ_{37}	0.55	0.87	0.79
PV	3.31	5.64	4.78

non-rotationally symmetric components only

	visible	EUV LSI	difference
σ_{37}	0.26	0.80	0.78
PV	1.99	5.47	4.40

First EUV alignment

Field measurement

M030806

σ_{37} [nm]

0.84	0.80	0.66
0.80	0.66	0.84
0.94	0.66	0.83

$\lambda/20.5$

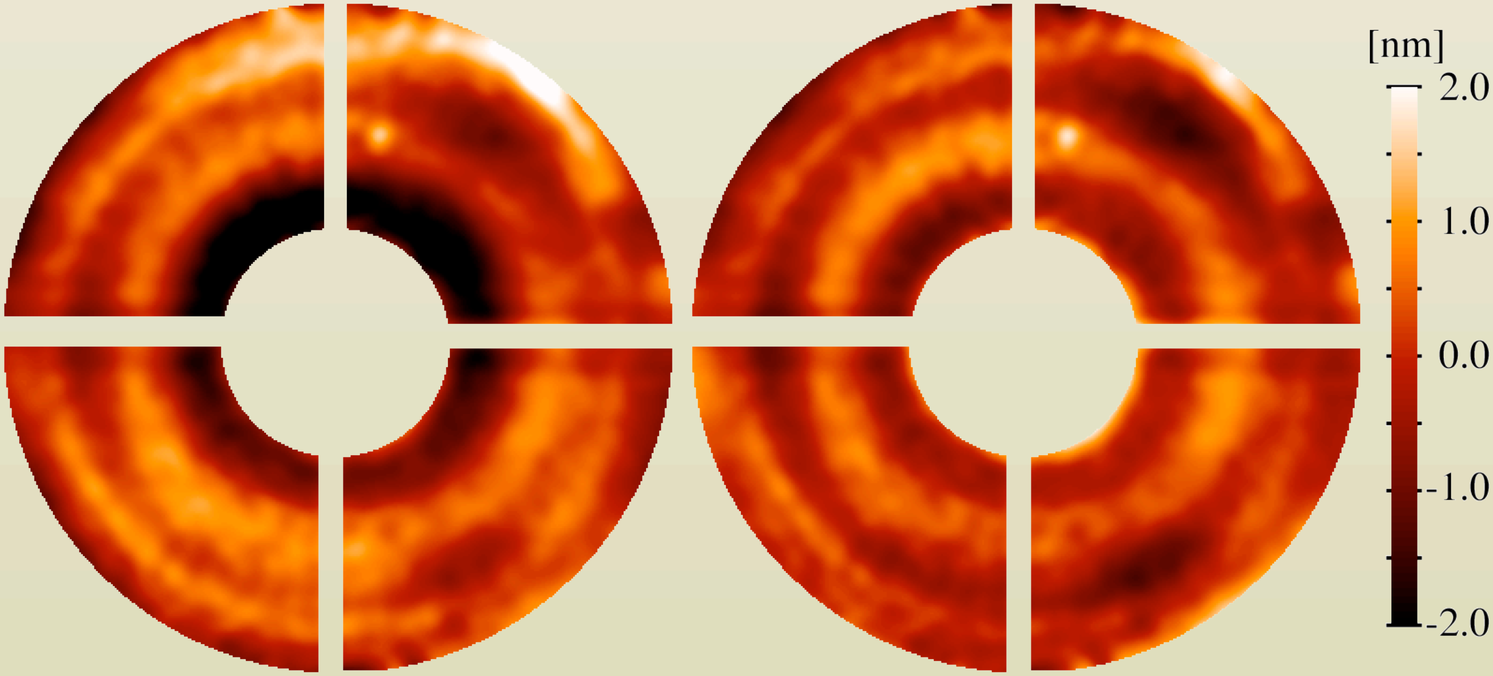
central
field point [nm]

astig = 0.05
coma = 0.08
sph. ab. = 0.02
trifoil = 0.22
h.-o. sph. = 0.34

Astigmatism, coma, and spherical aberration are sensitive to alignment and can be removed.

Adjustments are made to M1’s 6-arm mount: 0.03–2.50 µm step sizes.

PS/PDI measurements 2 days after LSI alignment



as-measured [nm]

σ_{37} = 0.68

PV = 3.54

astig. = 0.18

coma = 0.28

sph. ab. = 0.40

trifoil = 0.10

h.-o. s. = 0.30

"base" [nm]

σ_{37} = 0.45

PV = 2.92

With astigmatism, coma, and spherical aberration removed.

The system alignment had changed noticeably in 2 days.

System stability

The stability of every optical system is unique.

THEORY:

- **We believe small alignment actuations contribute to the instability.**
- **Vent/pump cycles may release stress.**
- **There is not enough data to draw firm conclusions.**

REMINDER:

- **These effects are small, not large.**
  Wavefront changes were a few tenths of a nm.

In-Situ Monitoring will be important

Second (and best) EUV alignment

Field measurement

M030925

σ_{37} [nm]

0.79	0.59	0.71
0.90	0.55	0.76
0.71	0.60	0.61

$\lambda/24.5$

central field point [nm]

astig = 0.04
coma = 0.06
sph. ab. = 0.04
trifoil = 0.14
h.-o. sph. = 0.37

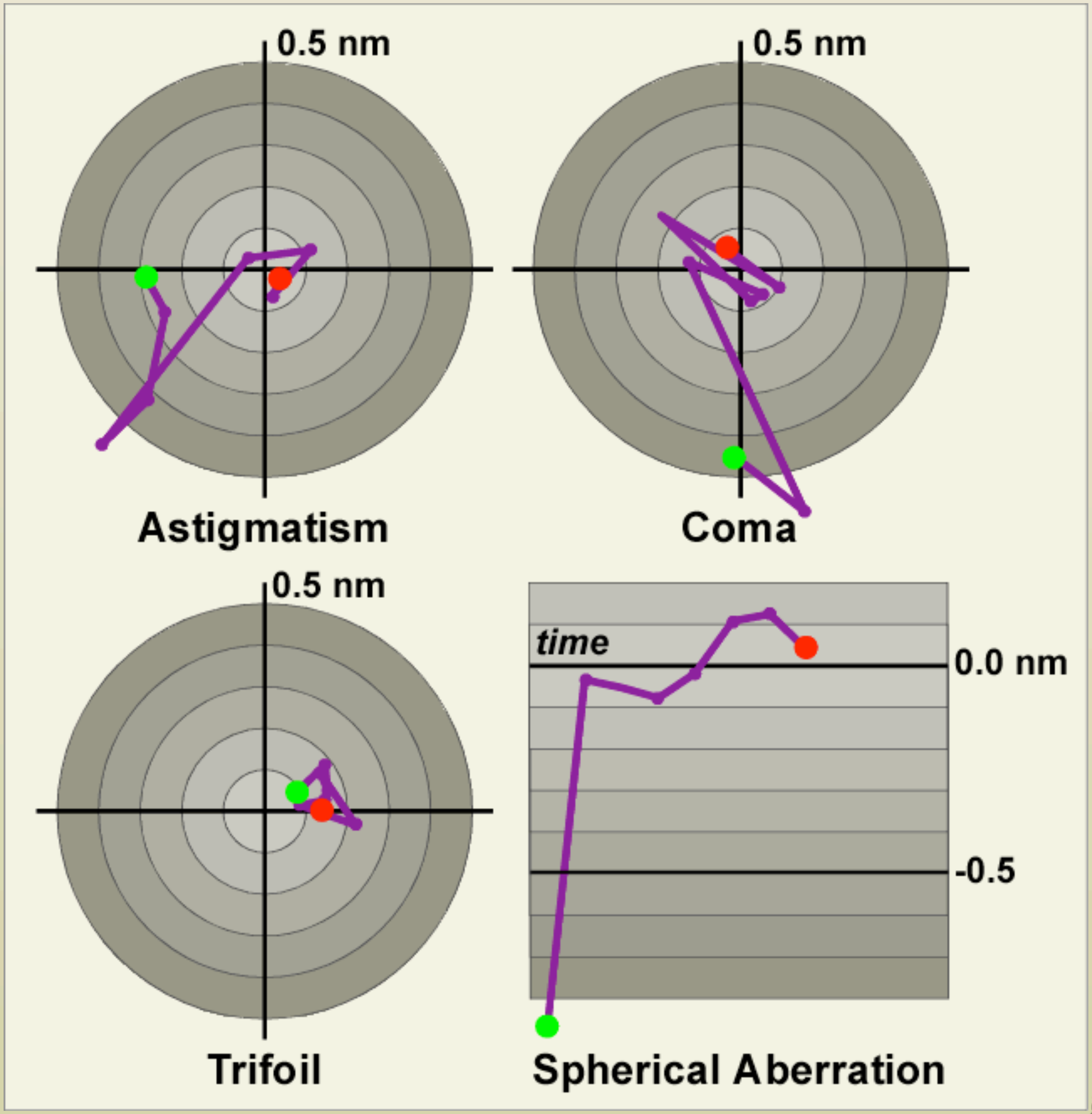
Following the installation of some imaging hardware, the optic was re-measured and re-aligned, achieving its best overall alignment.

Wavefront measurements during alignment

central field point

- Initial value
- Value following final alignment

Following initial alignment and measurement, the optic was removed and replaced in the chamber as components for imaging were installed.



Wavefront measurements during alignment

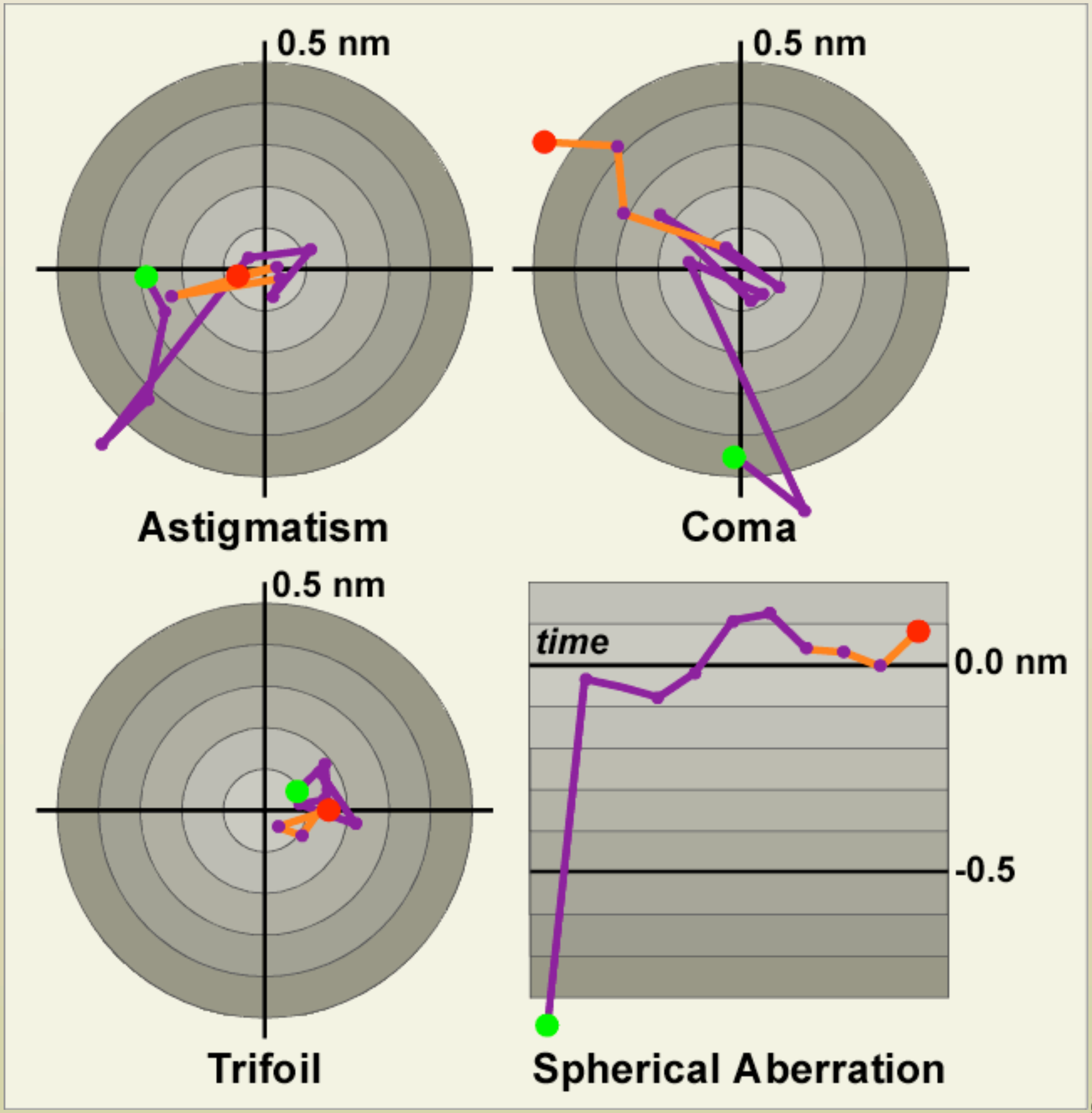
central field point

Initial value

Observed drift over 1 month

Last measured value

The cause of the drift was never established

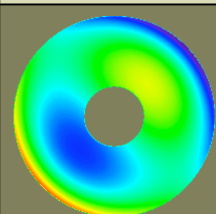
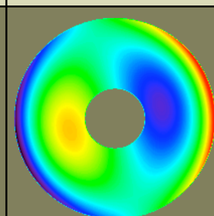
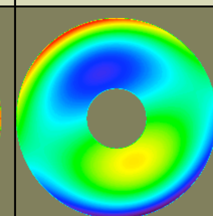
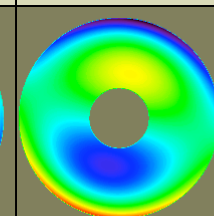
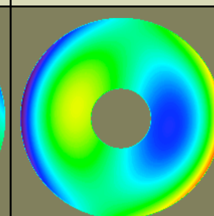
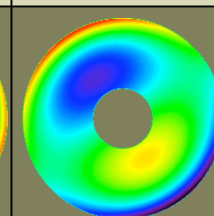


How sensitive is the wavefront to actuation?

Six arms support the M1 mirror.

A <u>1-µm</u> change in the arm length yields the following wavefront changes:

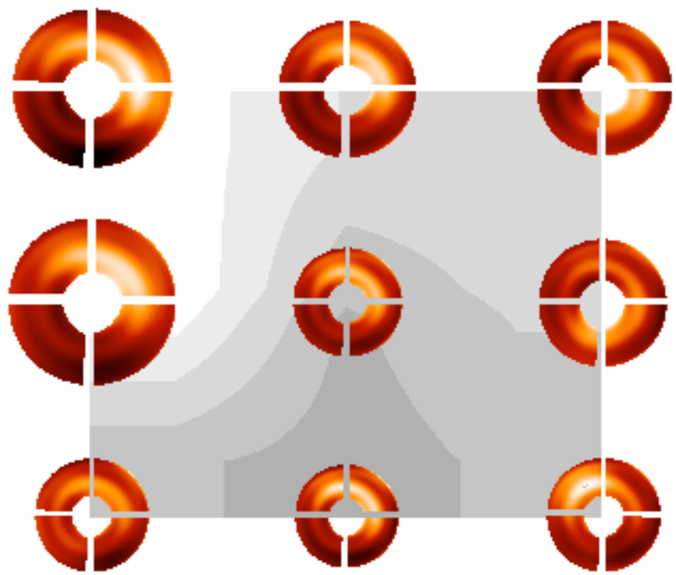
[nm]

aberration coefficient	Arm 1	Arm 2	Arm 3	Arm 4	Arm 5	Arm 6
coma	**3.191** **57.3°**	**2.765** **–167.8°**	**3.020** **–76.2°**	**3.047** **69.6°**	**3.323** **165.3°**	**2.647** **–44.3°**
astigmatism	0.192 –119.4°	0.213 156.2°	0.161 12.2°	0.177 85.2°	0.135 –21.2°	0.044* –121.7°
spherical aberration	0.071	0.069	0.071	0.100	0.065	0.082
Δ(Wavefront)						

Mirror actuation also affects the field position

Final alignment state of the optic

Field measurement



M031024

	σ_{37} [nm]	
1.16	1.00	0.99
1.22	0.80	0.94
0.83	0.76	0.83

$\lambda/17.8$

middle-bottom field point [nm]

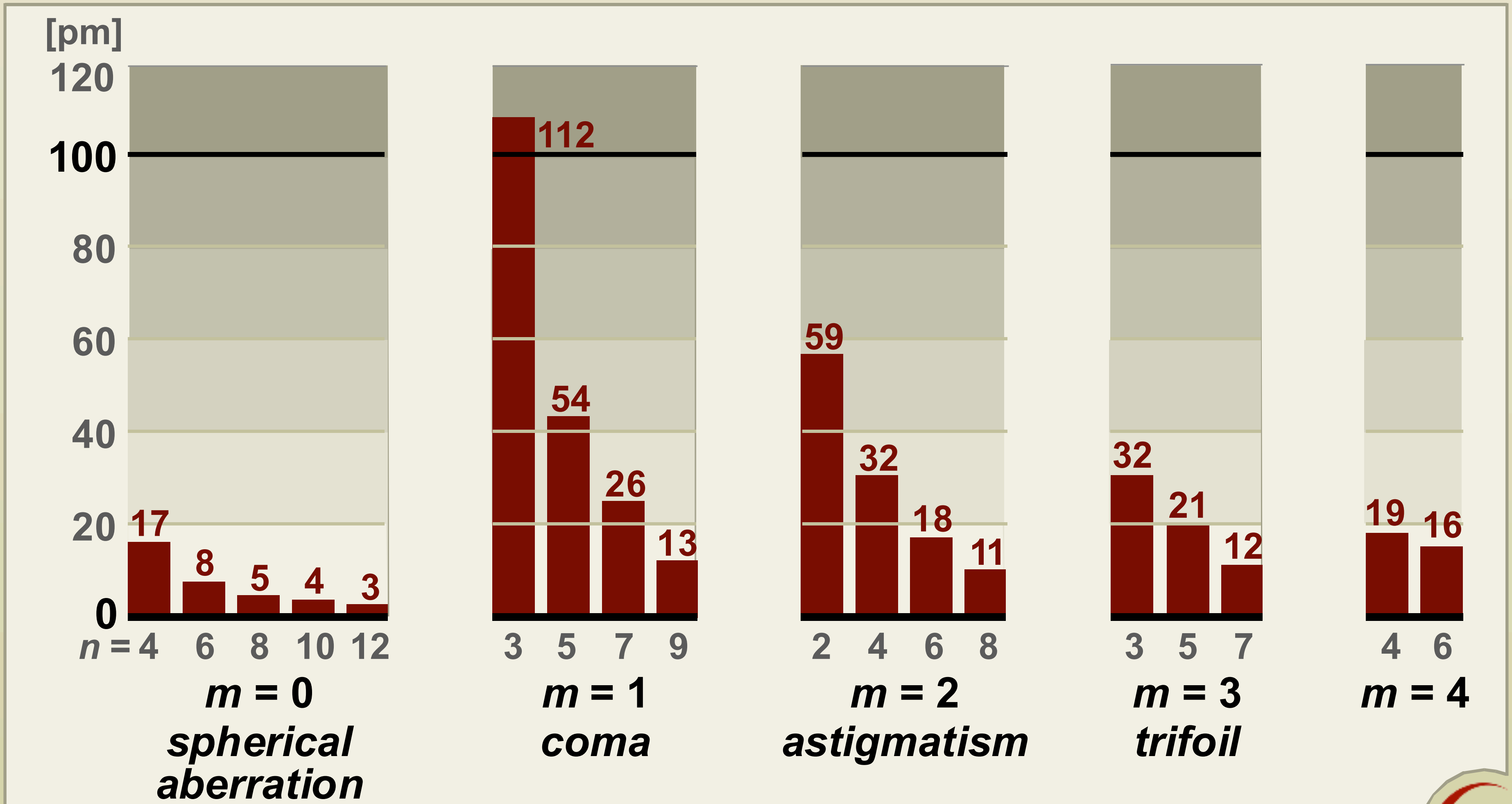
astig = 0.03
coma = 0.51
sph. ab. = 0.04
trifoil = 0.08
h.-o. sph. = 0.37

One month after the final alignment, the system had drifted slightly out of its optimized alignment

How precise or repeatable is shearing interferometry?

1) Instantaneous repeatability

The variation of the Zernike coefficients *within* a set of measurements — averaged over hundreds of measurement sets.



How precise or repeatable is shearing interferometry?

1) Instantaneous repeatability

The variation of the Zernike coefficients *within* a set of measurements — averaged over hundreds of measurement sets.

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2) Across-the-field measurements

We observed small, self-consistent variations from point to point despite:

(a) different pinholes

(b) Over 3 mm of system travel.

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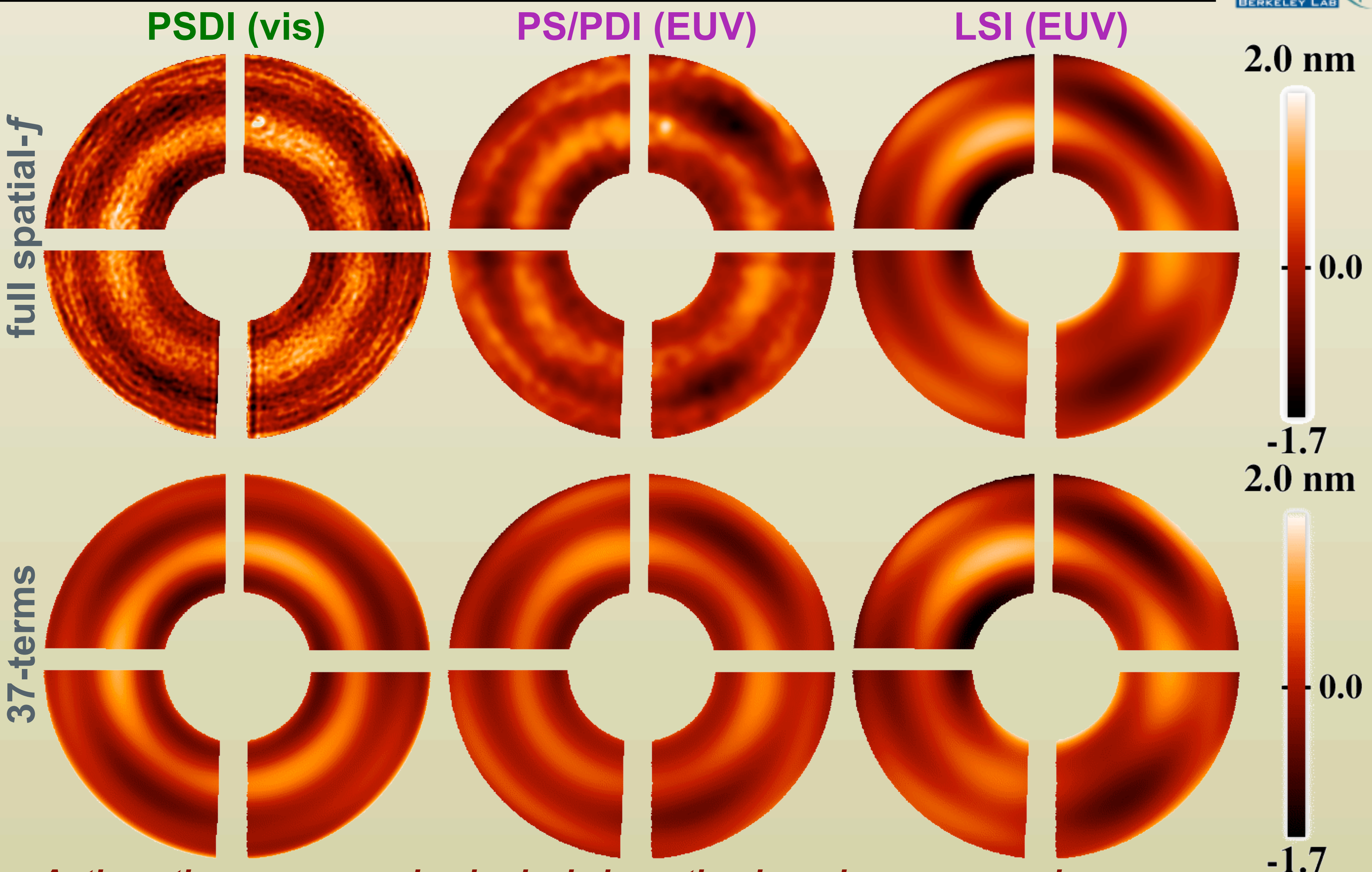
3) Measurement during alignment

System alignment to remove astigmatism, coma, spherical aberration requires stable, self-consistent measurements. We routinely achieved ~0.05-nm control.

Three-way comparison of “base” wavefronts



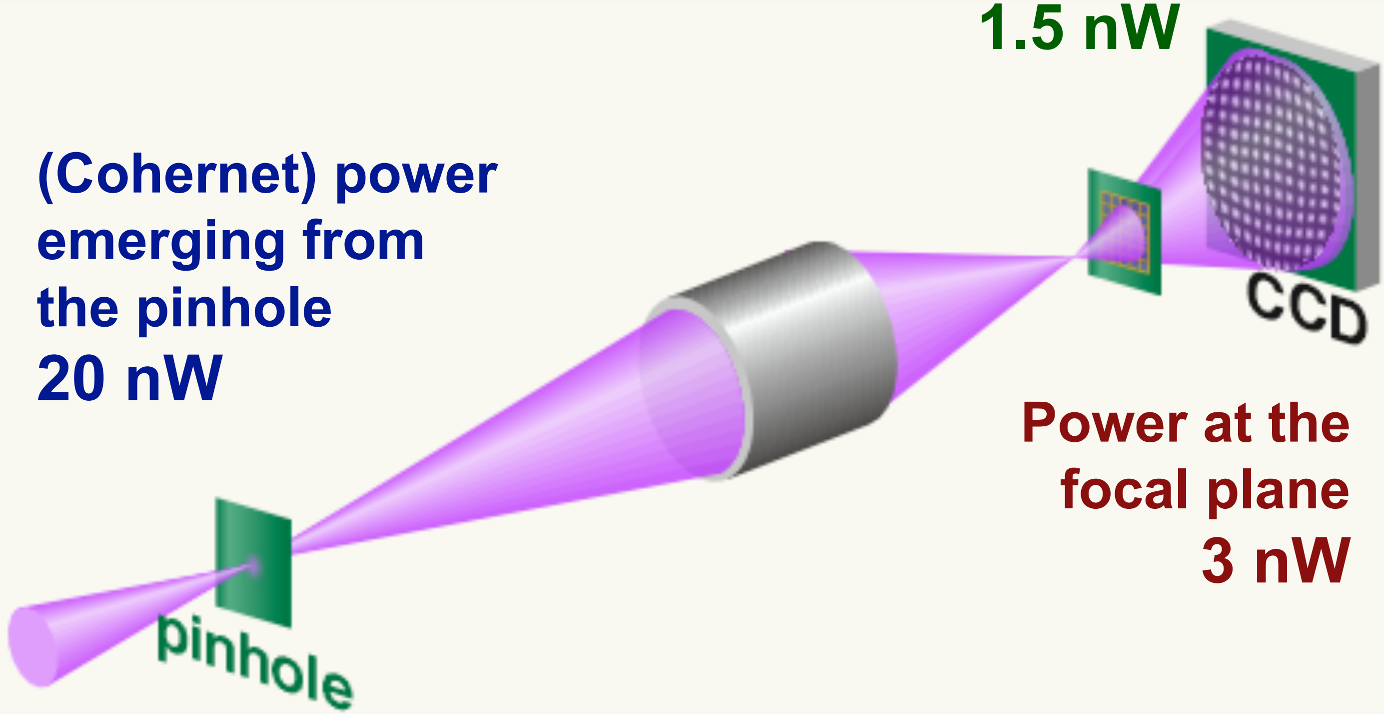
Astigmatism, coma, and spherical aberration have been removed for this comparison.

How much EUV power do you need for interferometry?

lateral shearing interferometer

Power reaching the CCD (~20 s exp.) 1.5 nW

(Cohernet) power emerging from the pinhole 20 nW

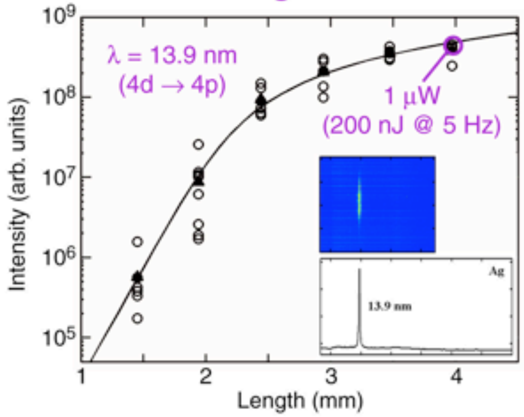


Power at the focal plane 3 nW

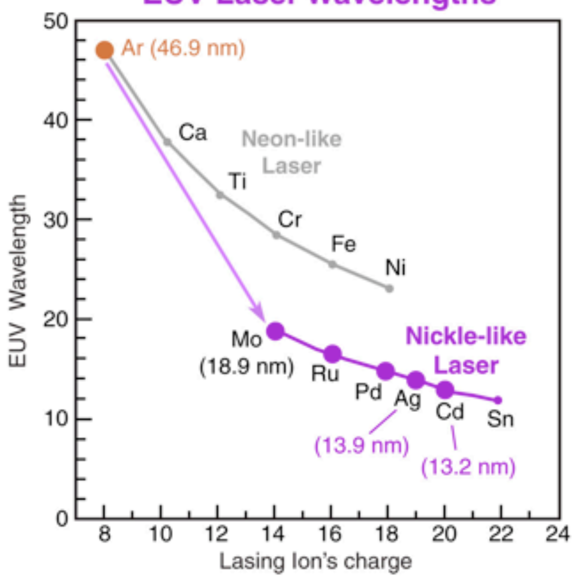
Compact, Coherent EUV Source Development at the New EUV Science & Technology Center

Colorado State University
Fort Collins
(Rocca, Menoni et al.)

Ni-like Ag EUV Laser

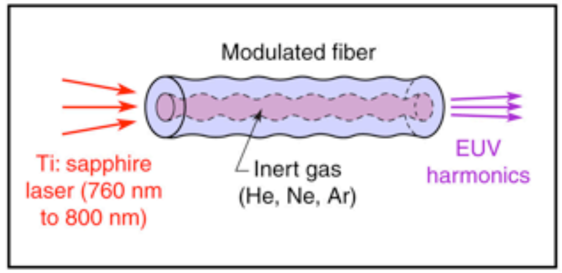


EUV Laser Wavelengths

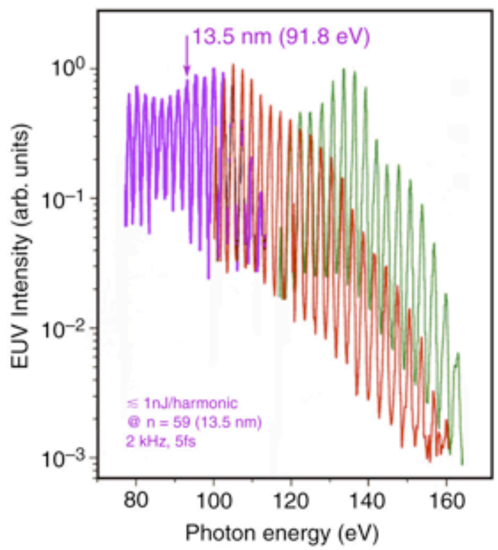


University of Colorado
Boulder
(Murnane, Kapteyn et al.)

EUV High Harmonic Generation (HHG)



Tunable EUV Harmonics



University of California
Berkeley & LBNL
(Attwood, Anderson et al.)

Applications to EUV Metrologies:

- Compact, at-wavelength EUV interferometry
- Compact, EUV source for defect inspection
- Compact, EUV sources for EUV microscopy
- Compact, EUV sources for resist development

Courtesy of
David Attwood

Conclusions

Successful EUV interferometry at 0.3 NA.

Repeated measurements made across the field during alignment optimization.

Interferometry, alignment brought the system to diffraction-limited wavefront quality: σ_{37} = 0.55 nm, λ_{EUV}/24.5

Alignment drift complicated measurements and comparisons.

Final wavefront at central field point: σ_{37} = 0.8 nm, λ_{EUV}/17.

Comparisons with PSDI (vis) showed consistent higher-order spherical aberration, but weak agreement in non-rotationally symmetric terms. LSI-to-PS/PDI comparison revealed subtle aspects of the data analysis that are undergoing further study.

Acknowledgment: Kim Dean, International SEMATECH